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TECHNICAL MEMORANDUM

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DESIGN PRINCIPLES FOR DEPOSIT-FREE INJECTORS FOR USE WITH BORON-CONTAINING FUELS

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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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DESIGN PRINCIPLES FOR DEPOSIT-FREE INJECTORS FOR USE WITH BORON-CONTAINING FUELS*

By Ralph T. Dittrich

SUMMARY

An experimental investigation was conducted to determine causes of deposits on fuel injectors and to develop design principles and operational procedure for deposit-free injectors. This study was confined to deposits from boron-containing fuels on simple-orifice and swirl-type injectors. Preliminary studies were conducted at cold-flow conditions with water as the injection fluid. Final injector designs were tested in a flame tunnel with a boron-containing fuel (HEF-2) at conditions simulating a turbojet afterburner operating at high-altitude cruise.

Deposition due to boron fuel was prevented on swirl-type injectors by application of a porous gas-stream deflector to modified injectors. Deposition on simple-orifice injectors was prevented only on an injector design that used pressure air.

INTRODUCTION

One of the problems in the application of boron-containing fuels to ramjet and turbojet afterburners is the rapid accumulation of solids from reaction products on the fuel injector (ref. 1). The present study was conducted at the NASA Lewis Research Center to formulate design principles and operational procedure for deposit-free fuel injectors.

Deposits from boron-containing fuels may result from either decomposition or combustion products. The products of fuel decomposition (at fuel temperatures above 100° to 250° F, depending on fuel type) form solids that may deposit internally as well as externally on fuel injectors. Combustion products (boric oxide) deposit as a solid at temperatures below approximately 900° F and as a viscous liquid at higher temperatures. Accumulation of such solids on fuel injectors interferes

*Title, Unclassified.

with the normal atomization and distribution of the fuel and results in deterioration of gas temperature profiles and combustion efficiencies and in large deposits on duct walls (ref. 2).

Fuel decomposition within fuel injector assemblies has been successfully prevented by air or gas shrouding of the injector (refs. 2 and 3), by thermal insulation (ref. 4), and by using a thermally stable preburn and purge fuel (compatible with the boron fuel used) immediately before and after each run with a boron-containing fuel (ref. 5). The present study, therefore, is concerned with deposits on the exterior of fuel injectors.

Tests were conducted in a 6- by 6-inch duct that served as an observation tunnel at cold-flow conditions and as a flame tunnel when using a boron-containing fuel. Because of the hazards involved in the combustion of boron fuels, the preliminary studies were conducted with water as the injection fluid. The factors causing injector deposition and the effects of design modifications were studied by means of visual observation of water injection. Modified injectors were tested with a boron-containing fuel in the flame tunnel at simulated high-altitude-cruise conditions of a turbojet afterburner. Design principles and operational procedure for deposit-free fuel injectors are discussed.

APPARATUS

Flame Tunnel

A schematic diagram of the test apparatus and associated ducting is shown in figure 1. Equipment for throttling, metering, and preheating the primary-air supply precedes the test section. When the test section is used as a flame tunnel, secondary air is mixed with the exhaust products upstream of the outlet-temperature-measuring station.

The test section consists of a 6- by 6-inch water-jacketed duct with a section of the wall and floor removable. For observation during cold-flow tests, the removable section was of transparent lucite. During combustion tests, lucite was replaced by metal plates.

The cold-flow deposition studies were conducted with water (at pressures up to 160 lb/sq in.) as the injection fluid. For certain cold-flow tests, a mixture of water and air was supplied to the injector by the arrangement shown in the schematic drawing of figure 2. The addition of air to the water flow was intended to simulate the effect of entrained fuel vapors or gases on injector spray characteristics.

For the combustion tests, a commercially available propyl pentaborane fuel (hereinafter designated HEF-2 fuel) was used with the pressurized fuel system shown in figure 3.

Injectors

Two types of fuel injectors were investigated (fig. 4): a swirl-type injector that projected downstream from an L-shaped mounting, and a simple orifice (directed downstream) in the wall of a tube. The injector supports were of double-wall construction in order to reduce heat transfer from the hot gas stream. The ratings of the swirl-type injectors used in the cold-flow tests varied from 10.0 to 40.0 gallons per hour (at 100 lb/sq in.), and their hollow-cone spray angles varied from 50° to 80°. Preliminary cold-flow studies with commercial swirl-type injectors indicated the need for smooth injector-body contours and the elimination of the plane surface in the region of the orifice. Accordingly, all swirl-type injectors used were modified as shown in figure 4(b). Because the injectors used in the cold-flow tests were of assorted capacities, the flow rates are expressed in terms of injection pressure instead of in volumetric flow rates. For the combustion tests only, the 15.3-gallon-per-hour, 60°-spray-angle injectors were used.

Gas-Stream Deflectors

Sketches of the various gas-stream deflectors investigated are presented in figures 5 and 6. Deflectors used with swirl-type injectors were of concentric-ring construction (fig. 5); those for simple orifices were fabricated of wire screen (fig. 6). Deflector porosity, defined as the ratio of free area to deflector total area, ranged from 0.23 to 0.64. The concave form (facing upstream) of the deflectors tends to shift the stagnation streamline of the approach stream toward the outer rim of the deflector and thereby increase the airflow at its center.

PROCEDURE

Because of the hazards involved in using HEF-2 fuels, the mechanics of injector deposition were studied first under cold-flow conditions with water as the injection fluid. Next, various gas-stream deflector designs, modified by application of aerodynamic principles, were evaluated under cold-flow conditions also. Finally, several modified injector assemblies were tested in the flame tunnel with HEF-2 fuel.

During the cold-flow tests, the air velocity was varied from 60 to 150 feet per second (test-section Reynolds number Re, 2.0 to 5.0×10^{5}). During combustion tests, air was preheated to approximately 1200° F with a resulting stream velocity of approximately 460 feet per second (test-section Re, 2.05×10^{5}). The test-section pressures were somewhat above (within 5 in. Hg) atmospheric pressure.

RESULTS

The results of the injector deposition study are presented in three parts: (1) observation of factors contributing to injector deposition, (2) development of stream-deflector devices, and (3) flame-tunnel tests of modified injectors with HEF-2 fuel.

Factors Contributing to Injector Deposition

Deposition characteristics of both the simple-orifice and the swirl-type injectors were similar at the various cold-flow conditions investigated and are summarized as follows:

(1) At water-injection pressures of less than 2 pounds per square inch, the flow, because of insufficient kinetic energy to overcome adhesive forces, is not ejected from the orifice but instead forms a pool in the region of the orifice, the surplus being entrained by the airstream along the sides of the injector body at the line of flow separation. This condition may occur during startup and shutdown.

(2) At injection pressures from 2 to approximately 12 pounds per square inch, a solid jet emerges from the simple orifice (a conical sheet from the swirl-type injector) for a distance of approximately 1/2 inch, where breakup into droplets occurs. These droplets have insufficient kinetic energy to overcome the recirculating forces of the air vortexes formed in the wake of the injector body and are, therefore, entrained by the recirculating currents and impinge on the injector body. Surveys show that behind long cylinders mounted axially in a duct the recirculation zone extends 1.7 cylinder diameters downstream (ref. 6) while for long flat plates mounted normal to the duct the zone extends 2.8 plate widths downstream (ref. 7). For a cylinder mounted normal to the duct, the extent of the zone is probably within these values. This indicates that the present recirculation zones extend 0.8 to 1.06 inch downstream of the injector. The region where the solid jets (or sheets) were observed to disintegrate into droplets (at injection pressures below 12 lb/sq in.) was well within the recirculation zone.

(3) At pressures in the range of approximately 12 to 160 pounds per square inch, impingement of spray droplets on the injector did not occur regardless of airstream velocity, injector type, or capacity investigated. Certain injectors, however, did form a pool of water around the orifice at the high flow rates. Subsequent inspection of these injectors revealed minute burrs and cavities at the orifice exit.

(4) The injection of a water-plus-air mixture resulted in rapid fluctuations in injector pressures, discontinuities of the flow, and a rapid variation of the spray dispersion angle. The intensity of the

fluctuations varied with the injection pressure level. With the heterogeneous flow, spray impingement occurred on certain injectors only. Inspection revealed that injectors having tapered or rounded orifice exits suffered impingement, while those having clean, square, sharp-edged exits did not.

These cold-flow studies indicate four requirements for the solution of the deposition problem: (1) imparting additional kinetic energy to the injection fluid when at very low injection pressures, (2) controlling recirculation in the wake of the injector body, (3) using injectors having clean, square, sharp-edged orifice exits and streamlined outer bodies, and (4) eliminating compressible gases from the liquid discharge. Previous combustion tests with boron-containing fuels (refs. 5 and 4) suggest the following two additional requirements: (5) employing a preburn and purge procedure for the fuel system, and (6) maintaining a low fuel temperature in the injection system consistent with the thermal stability of the fuel. The use of a preburn fluid reduces injector temperature and sweeps out compressible gases, while the purge fluid prevents boron fuel dribbling at shutdown and the stagnation of the unstable fuel in the injector system where heat and exposure (at the orifice exit) may cause decomposition.

Development of a method for meeting requirements (1) and (2) is presented herein; items (3) to (6) are beyond the scope of this report.

Development of Deflector Design

A possible solution to the first requirement suggests deflecting part of the duct-gas stream around the trailing surface of the injector so as to entrain any efflux from the orifice. Any deflector, however, must necessarily obstruct a stream area greater than the cross-sectional area of the injector body itself and would, therefore, induce larger recirculation zones in its wake. This increases the importance of the second item, namely, controlling recirculation. Since the size of the recirculation zone is a function of baffle size, a deflector constructed of many small baffles should have a correspondingly short recirculation zone. Thus, the recirculation zone behind 0.020-inch-diameter wire baffles would be only 0.056-inch long, provided the free area between wires is sufficient to prevent recirculation due to the whole of the deflector. Reference 8 shows negligible wake velocity fluctuations (no formation or shedding of vortexes due to the whole of the baffle) behind perforated plates for free-area ratios (ratio of free area to total deflector area) of 0.4 and greater.

Cold-Flow Deflector Tests

Deflectors for swirl-type injectors. -

Effect of free-area ratio: The objective of the deflector porosity study was to eliminate recirculation behind the injector body without introducing a recirculation zone due to the deflector itself. The effect of porosity on deflector performance was studied with deflectors 1, 2, and 3 (fig. 5). With deflector 1 (free-area ratio, 0.64) recirculation occurred behind the injector only (droplet impingement on injector face), while with deflector 3 (free-area ratio, 0.28) recirculation occurred behind the deflector also (droplet impingement on both deflector and injector face). Deflector 2 (free-area ratio, 0.52), however, showed no evidence of recirculation behind either deflector or injector.

Effect of diameter and spacing: Entrainment of orifice efflux when at very low injection pressures requires that a high-velocity airstream sweep the orifice exit. Because of the porosity of the deflector, only a fraction of the deflected air is directed toward the fuel orifice. Control of this fraction of the airflow is a function of inner-ring location (ring diameter and distance from injector body) relative to the orifice exit.

Efflux entrainment was studied with deflectors having inner-ring diameters ranging from 0.156 to 0.430 inches (deflectors 2, 4, 5, 6, and 7, fig. 5) and spacings ranging from 0.020 to 0.115 inch. The criterion for satisfactory entrainment was the absence of any injection fluid on the injector exterior surface under all test conditions. Complete entrainment was obtained only with deflectors having the smallest inner diameter (0.156 in. diam., deflectors 4 and 6) and spaced within the range from 0.040 to 0.062 inches from the injector. Wide injector spray angles may require the closer spacing in order to prevent direct fuel impingement on the inner ring.

Deflector outer diameter is best expressed as the ratio of deflector to injector diameters. Within the range (2.0 to 2.6) investigated, no effect of outer diameter ratio on deflector performance was observed.

Deflectors for simple orifices. - The airstream deflectors used with simple orifices in a tube wall were of the type shown in figure 6. Modifications include variations in screen porosity, spacing from injector tube, and distance between the two deflector sections. Complete entrainment of low-energy efflux at the orifice exit was not obtained with this design. At the low injection pressures, the orifice outflow was observed to spread vertically along the trailing surface of the tube. Because of the continuous curvature of the tube wall, flow separation of the opposing deflected airstreams occurs and thereby forms a stagnation zone along the trailing surface of the tube.

A design of simple-orifice injector utilizing pressure air is shown in figure 4(d). The concentric ejection pattern of liquid surrounded by a high-velocity airstream entrains all orifice efflux and improves atomization. No deposition occurred on the injector assembly at any of the conditions investigated. However, at zero liquid flow, the pressure air caused a back pressure on the fuel system. This may be hazardous with a fuel supply system containing a boron fuel.

E-543

Flame-Tunnel Tests

Swirl-type injectors. - In order to verify the cold-flow observations, selected configurations were tested in the flame tunnel with HEF-2 fuel. Photographs of the injector assemblies, taken after each test, are reproduced in figures 7 to 11.

Deposition on swirl-type and simple-orifice injectors having no airstream deflectors is shown in figure 7. The reproductions show deposition due to recirculation in the wake of the injector body. During 3 minutes of operation with HEF-2 fuel, the swirl-type injector (fig. 7(a)) had accumulated just sufficient deposits to interfere with the normal spray pattern. After the onset of spray interference, deposition is generally greatly accelerated.

The effect of deflector porosity on deposition characteristics is shown in figure 8. As noted in cold-flow tests, deflectors with a free-area ratio of 0.64 (configuration 1, fig. 8(a)) show recirculation in the wake of the injector, while those with a free-area ratio of 0.28 (configuration 3, fig. 8(b)) show recirculation due to blockage of the deflector. In addition, figure 8(b) shows decomposition products at the orifice exit, the result of not purging the fuel system after the test.

Figure 9 is of interest in illustrating the growth of deposition due to incomplete entrainment (inner-ring diameters too large) on deflectors 2 and 7 during 5 minutes of operation with HEF-2 fuel.

Two flame-tunnel tests were made with configurations that showed no deposition tendencies during their cold-flow investigation (fig. 10). In the first test, deflector 6 was run singly for 10 minutes duration at 120 percent of injector rated capacity (flame-tunnel equivalence ratio, 0.151). In the second test, three deflectors (two of no. 6 and one of no. 4) were run simultaneously for 18 minutes duration at 90 percent of injector rated capacities (equivalence ratio, 0.353). A preburn and purge procedure using a dry JP-type fuel was employed.

No deposition due to HEF-2 fuel occurred on these configurations excepting the small formation at one side of the orifice of the configuration in figure 10(d). This may have been due to the eccentric mounting of the deflector. The sooty coating on the injector bodies is due to combustion products from the inlet-air preheater. Note that the configuration of figure 10(b) had a foreign particle lodged in the fuel orifice that interfered with the normal spray pattern.

Simple-orifice injector. - Similar to cold-flow observations, no deposits were obtained during combustion tests with the air-atomizing type of simple-orifice injectors (fig. 11). The atomizing-air mass-flow rate was approximately 150 percent of fuel-flow rate.

Since complete liquid entrainment from simple orifices could not be attained with stream-air deflectors during cold-flow tests, these configurations were not included in the combustion tests.

CONCLUSIONS

Factors causing injector deposition and the effects of injector design modification were studied experimentally with simple-orifice and swirl-type injectors. Water was used as the injector fluid in preliminary cold-flow tests, and a boron-containing fuel (HEF-2) was used in the flame-tunnel tests of final injector designs.

The cold-flow injector studies indicate four requirements for the solution of injector deposition problems: (1) imparting additional kinetic energy to the injection fluid when at very low injection pressures, (2) controlling recirculation in the wake of the injector body, (3) selecting injectors having nontapered, clean, sharp-edged orifice exits and streamlined outer bodies, and (4) eliminating compressible gases from the liquid-fuel discharge. A method that meets requirements (1) and (2) was developed in the present investigation.

Application of a gas-stream deflector to swirl-type injectors resulted in complete entrainment of injector discharge at low injection pressures.

Recirculation due to both the injector body and the whole of the deflector was eliminated by making the deflector porous.

Application of the gas-stream deflection principle to simple orifices in a tube wall, however, had little effect on entrainment of low-pressure injector discharge. Only with an air-atomizing type of simple orifice, utilizing pressure air, was complete entrainment obtained.

Previous combustion tests with boron-containing fuels indicate the need for maintaining a low fuel temperature in the injector assembly and using a preburn and purge procedure. Flame-tunnel tests with HEF-2 fuel confirm the results of both the present cold-flow studies and the previous boron-fuel combustion tests.

Lewis Research Center
National Aeronautics and Space Administration
Cleveland, Ohio, August 18, 1959

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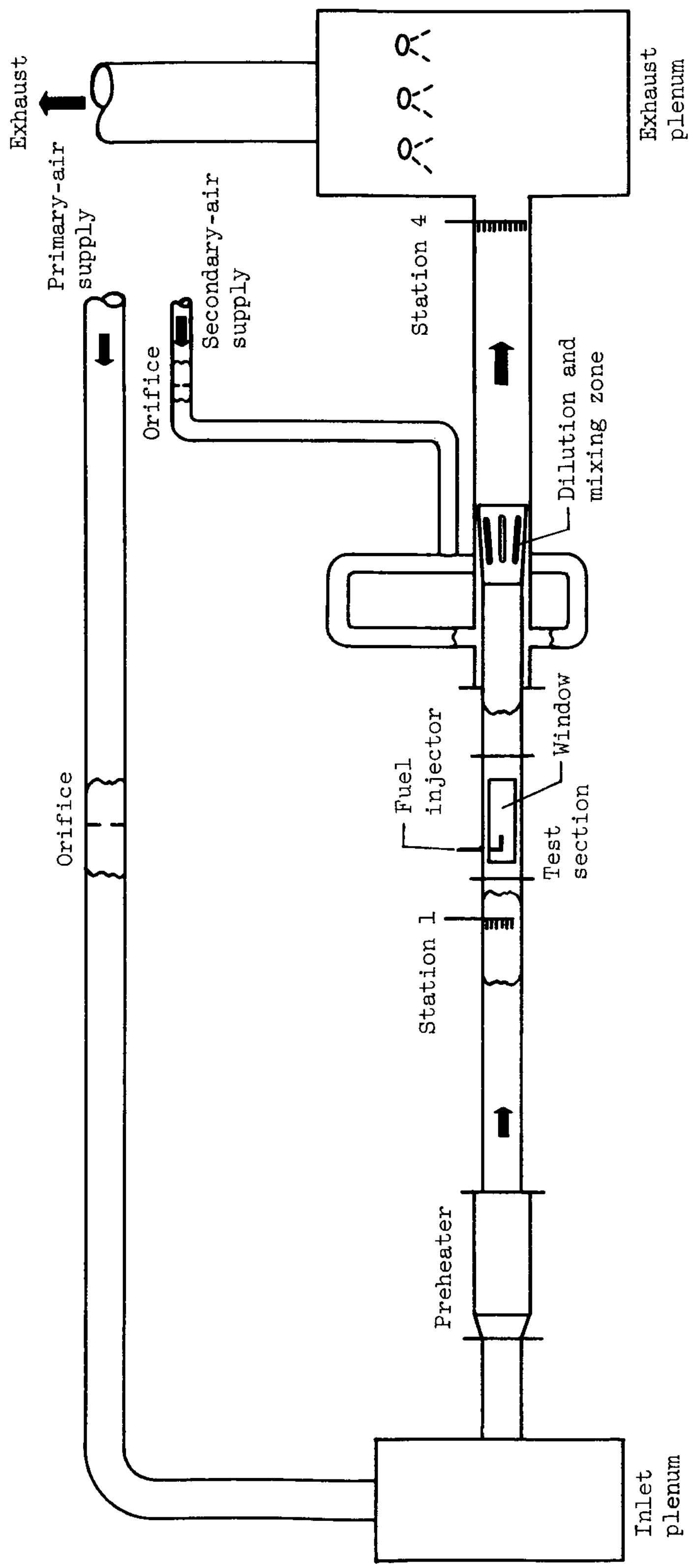


Figure 1. - Test apparatus.

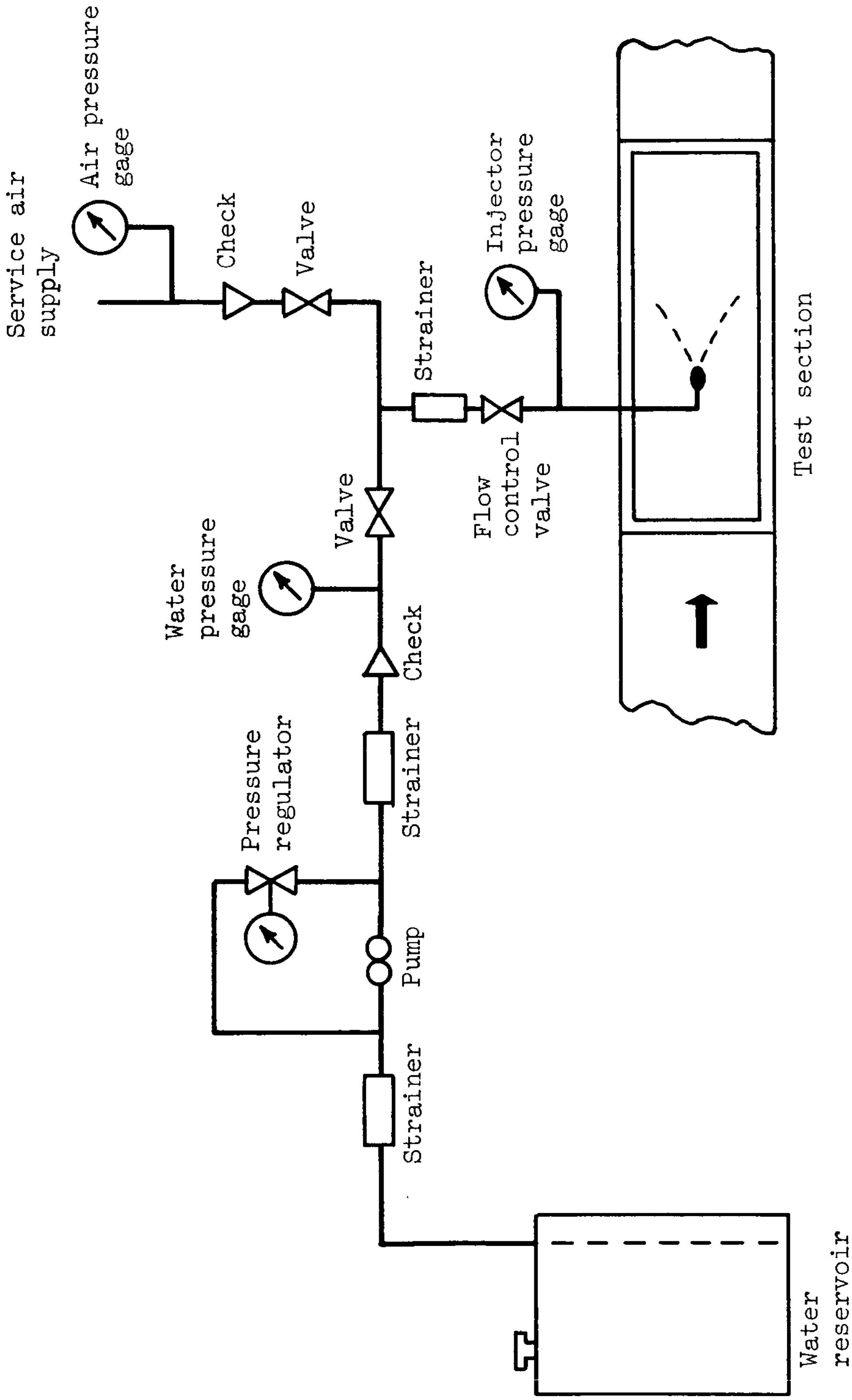


Figure 2. - Water-injection system.

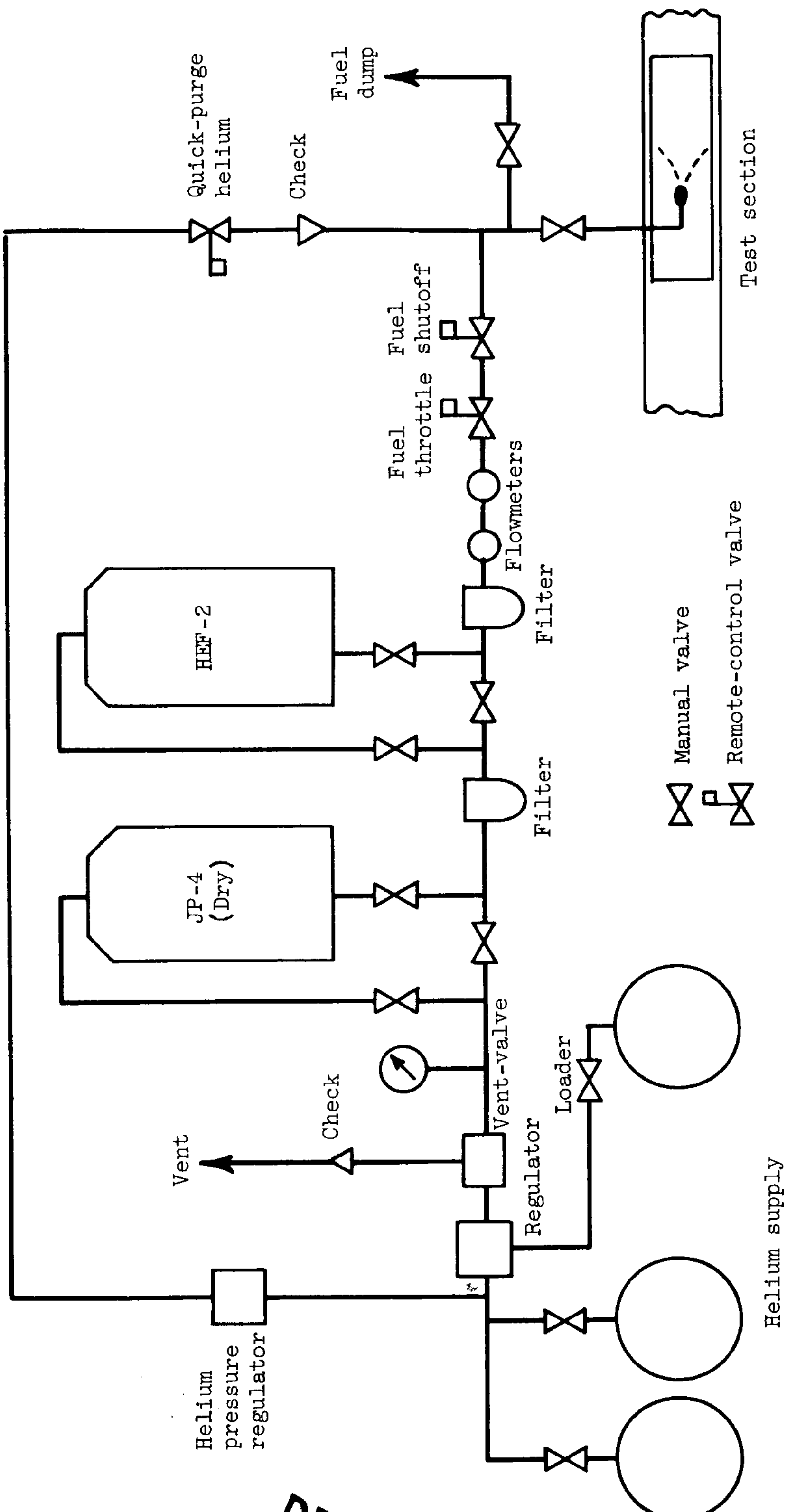
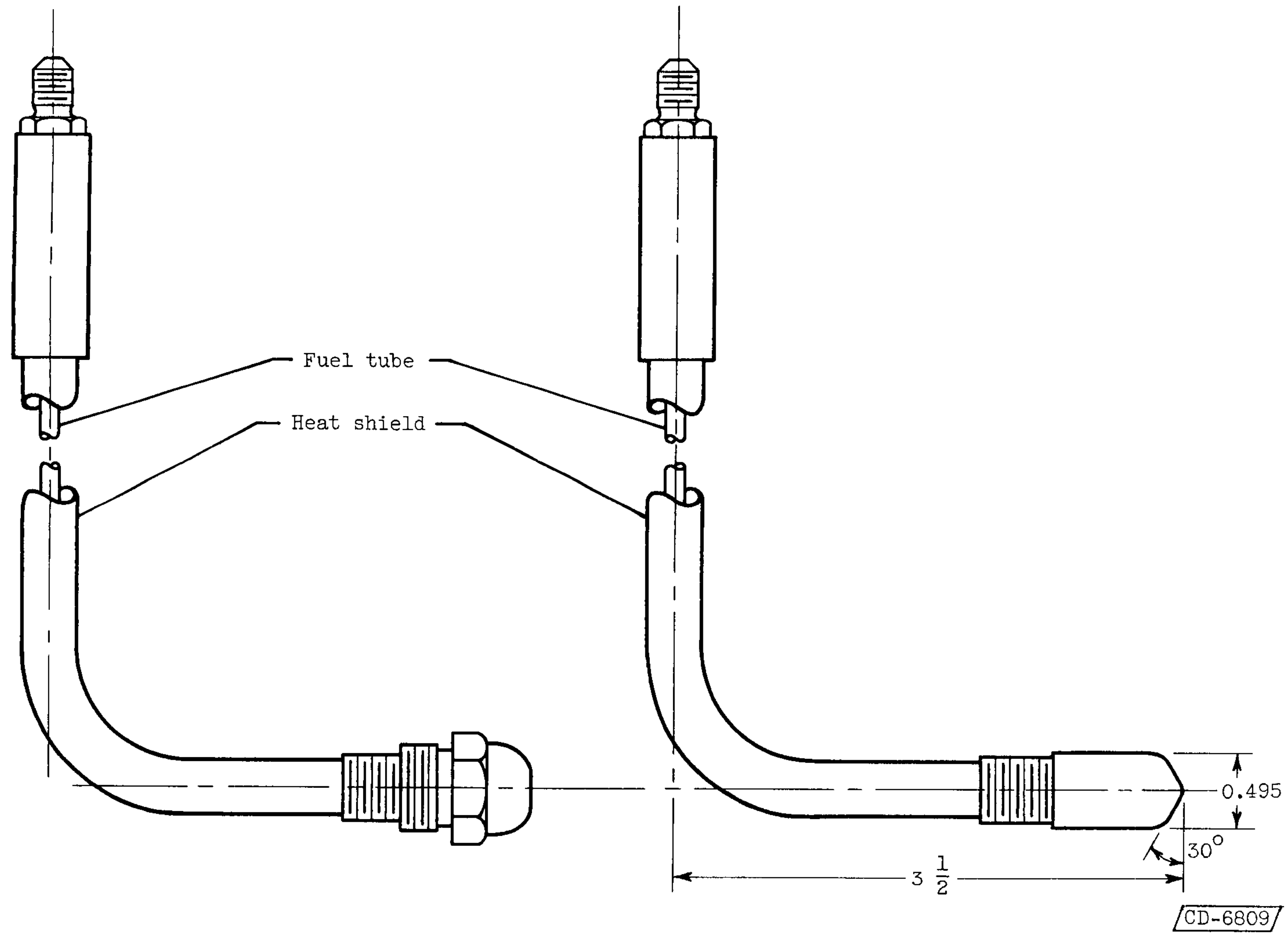


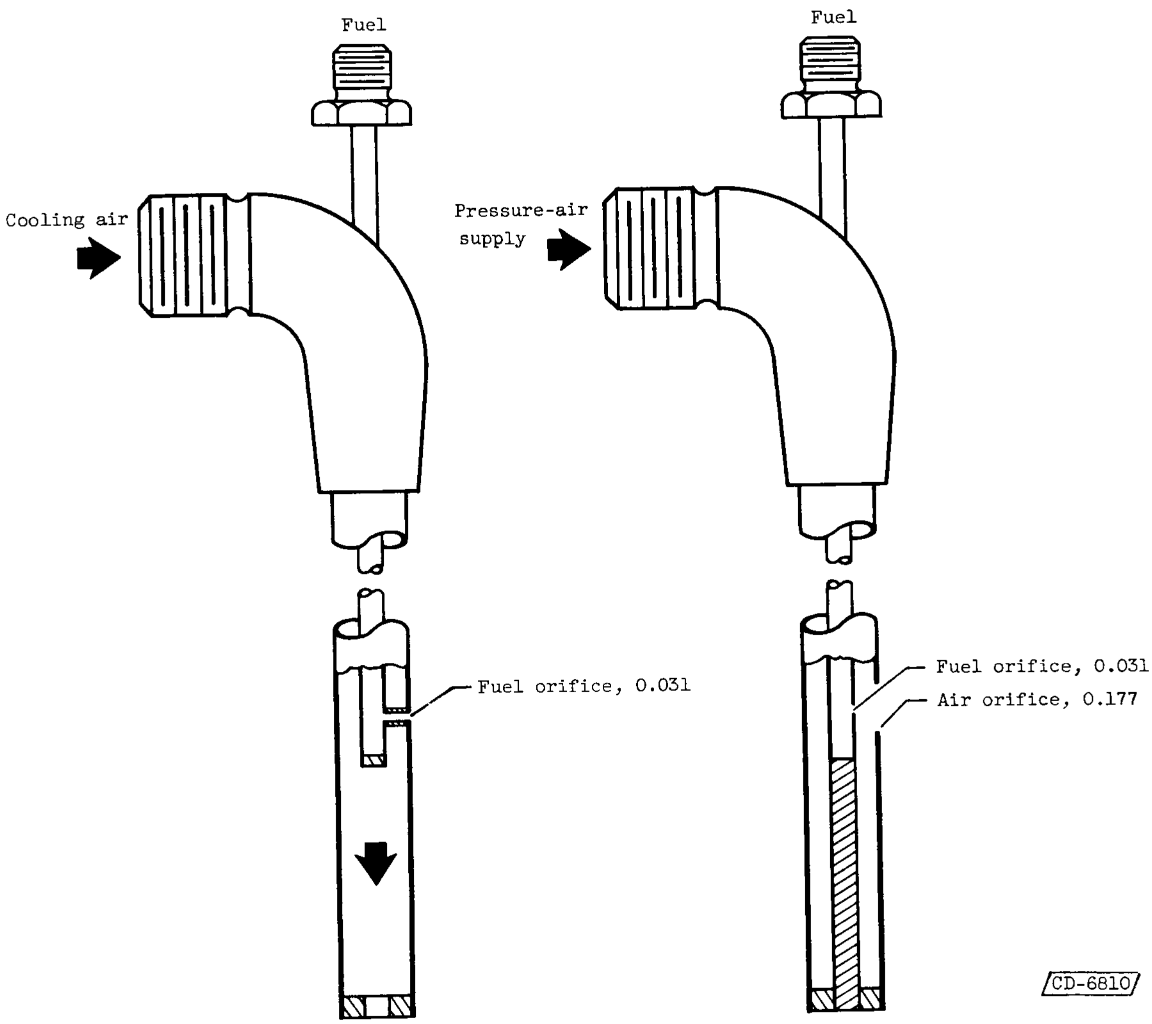
Figure 3. - Fuel system for HEF-2 fuel.



(a) Commercial swirl-type injector.

(b) Injector modified by streamlining outer body.

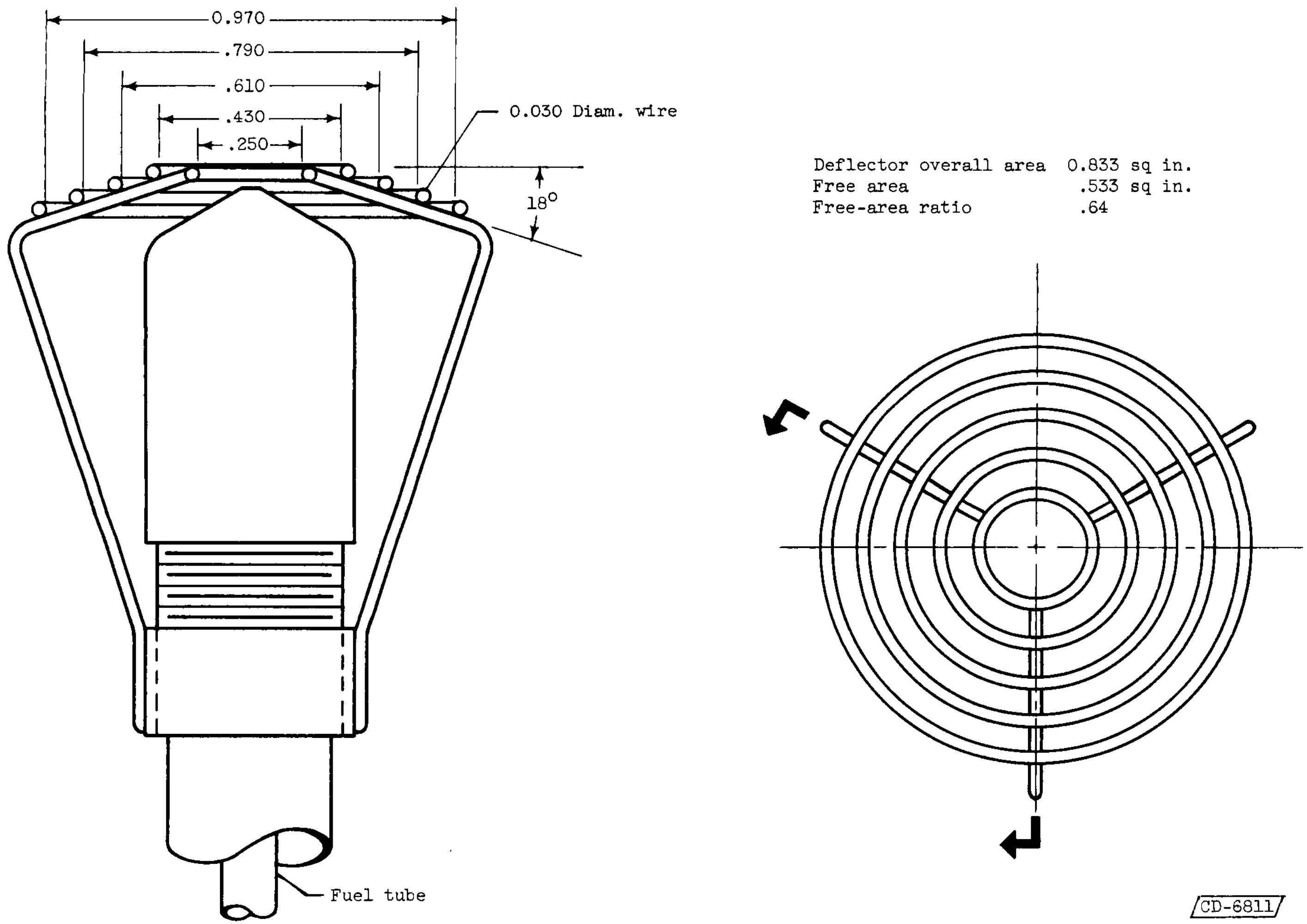
Figure 4. - Injectors used in cold-flow tests. (All dimensions in inches.)



(c) Simple-orifice injector.

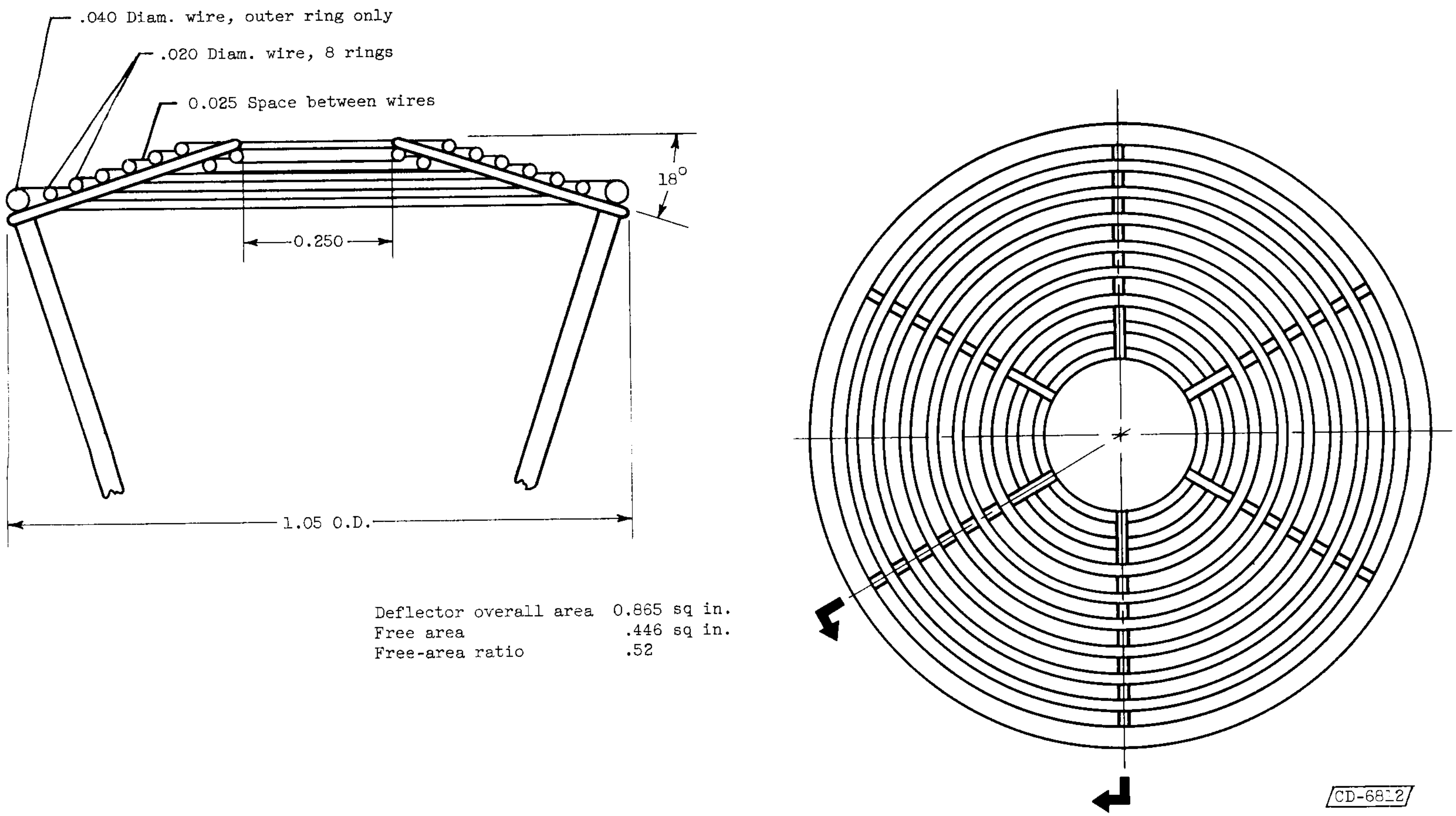
(d) Air-atomizing injector.

Figure 4. - Concluded. Injectors used in cold-flow tests. (All dimensions in inches.)



(a) Deflector 1.

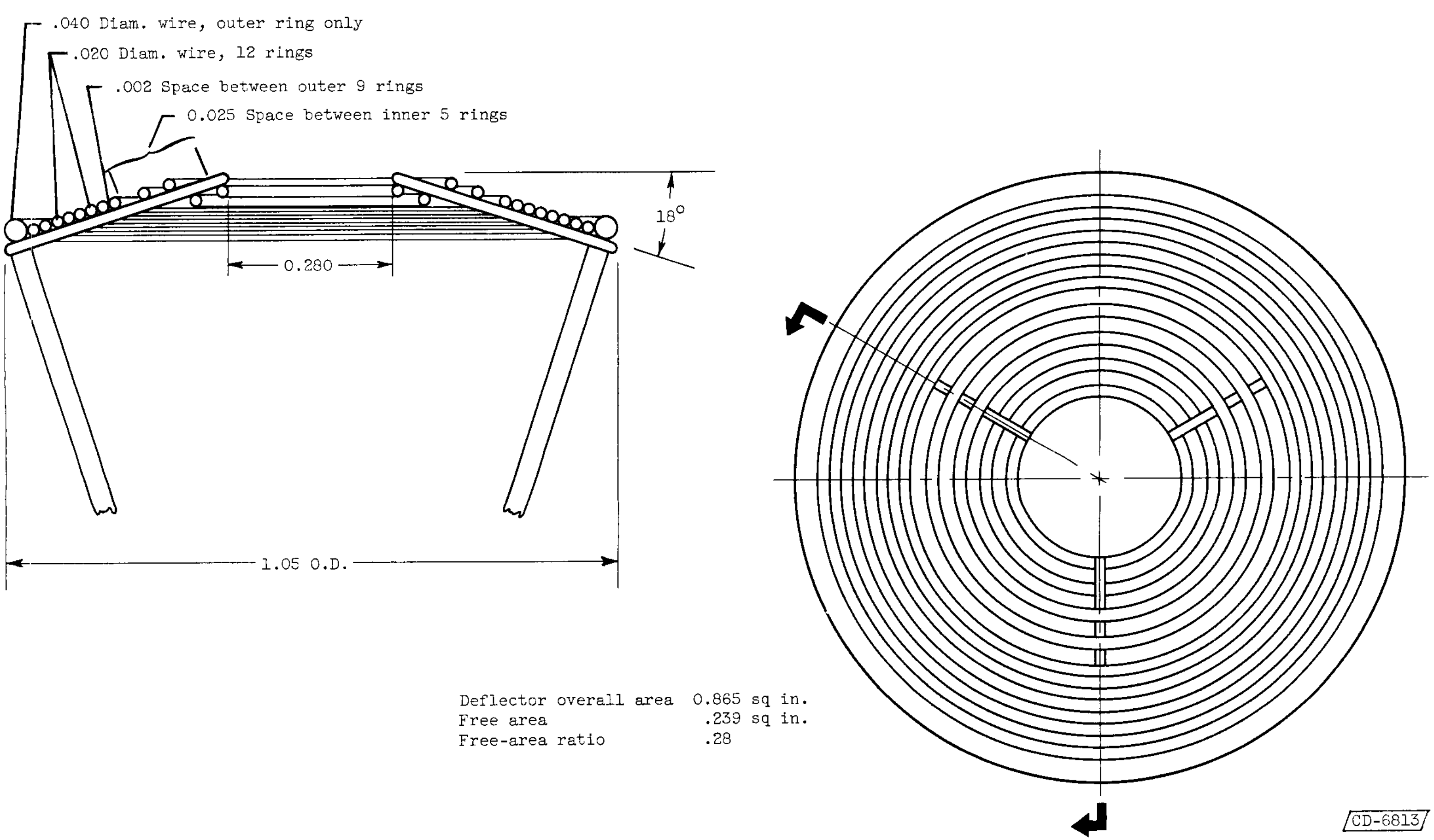
Figure 5. - Deflectors for swirl-type injectors. (All dimensions in inches.)



Deflector overall area	0.865 sq in.
Free area	.446 sq in.
Free-area ratio	.52

(b) Deflector 2.

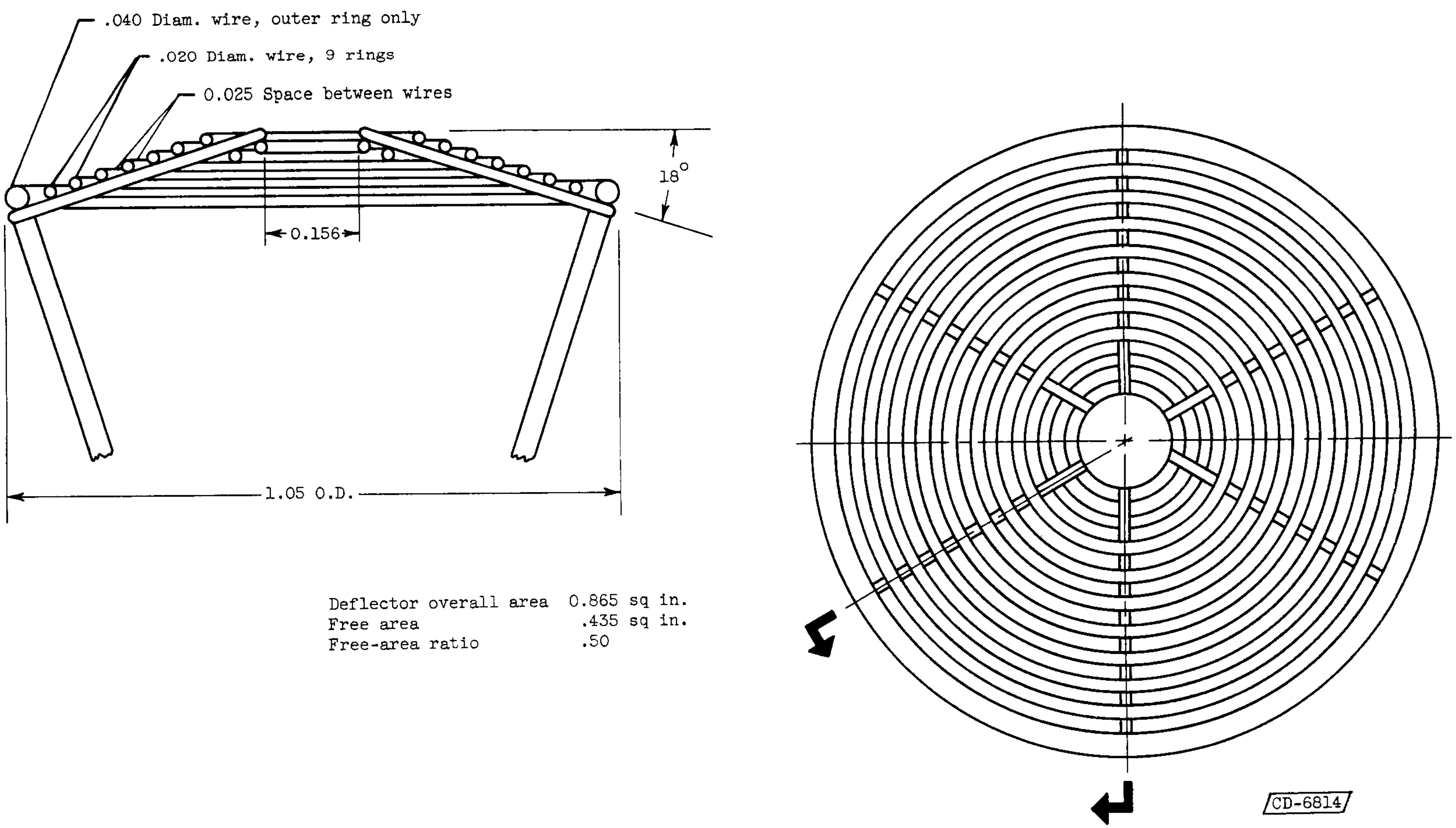
Figure 5. - Continued. Deflectors for swirl-type injectors. (All dimensions in inches.)



Deflector overall area 0.865 sq in.
Free area .239 sq in.
Free-area ratio .28

(c) Deflector 3.

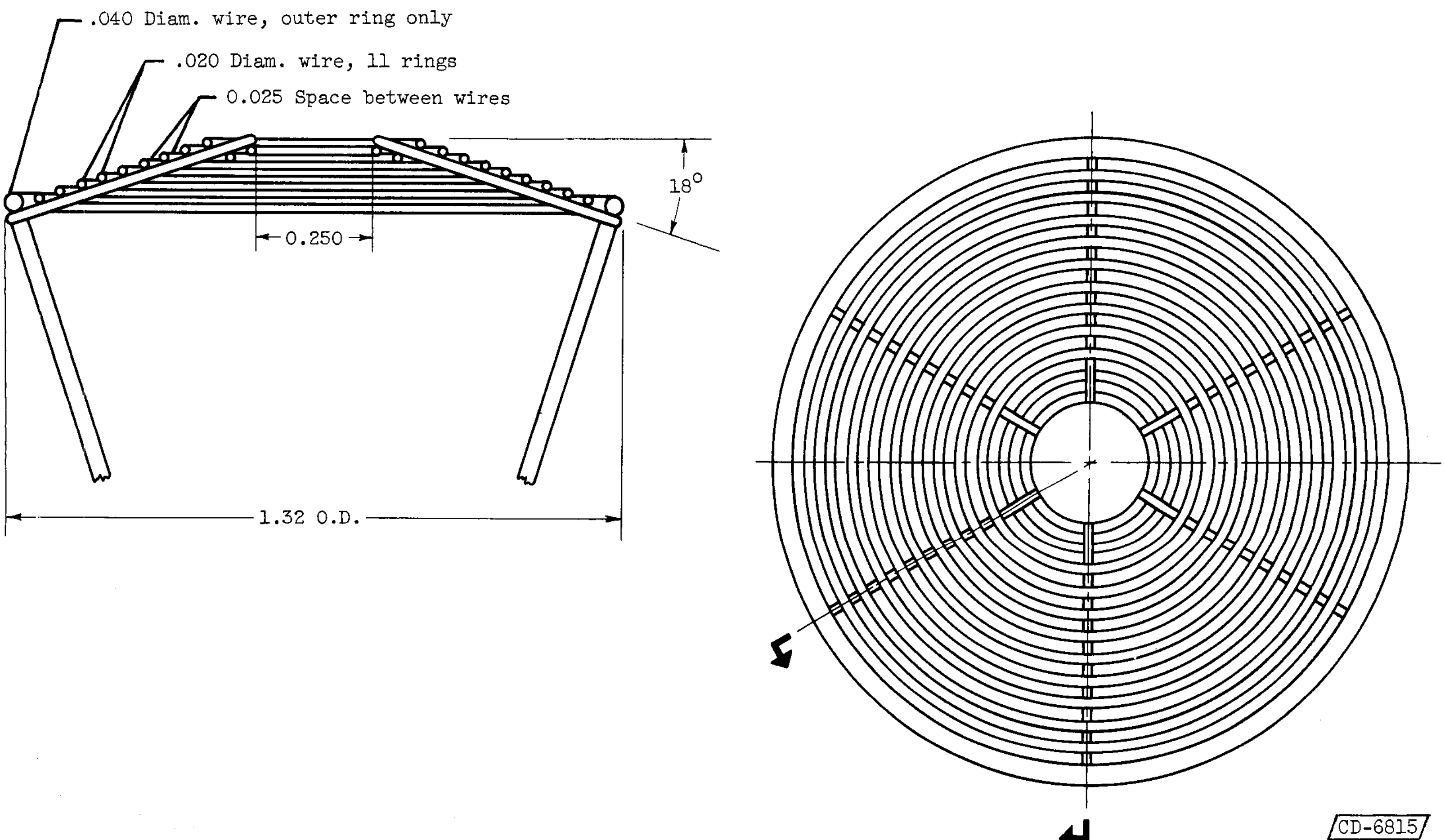
Figure 5. - Continued. Deflectors for swirl-type injectors. (All dimensions in inches.)



(d) Deflector 4.

Figure 5. - Continued. Deflectors for swirl-type injectors. (All dimensions in inches.)

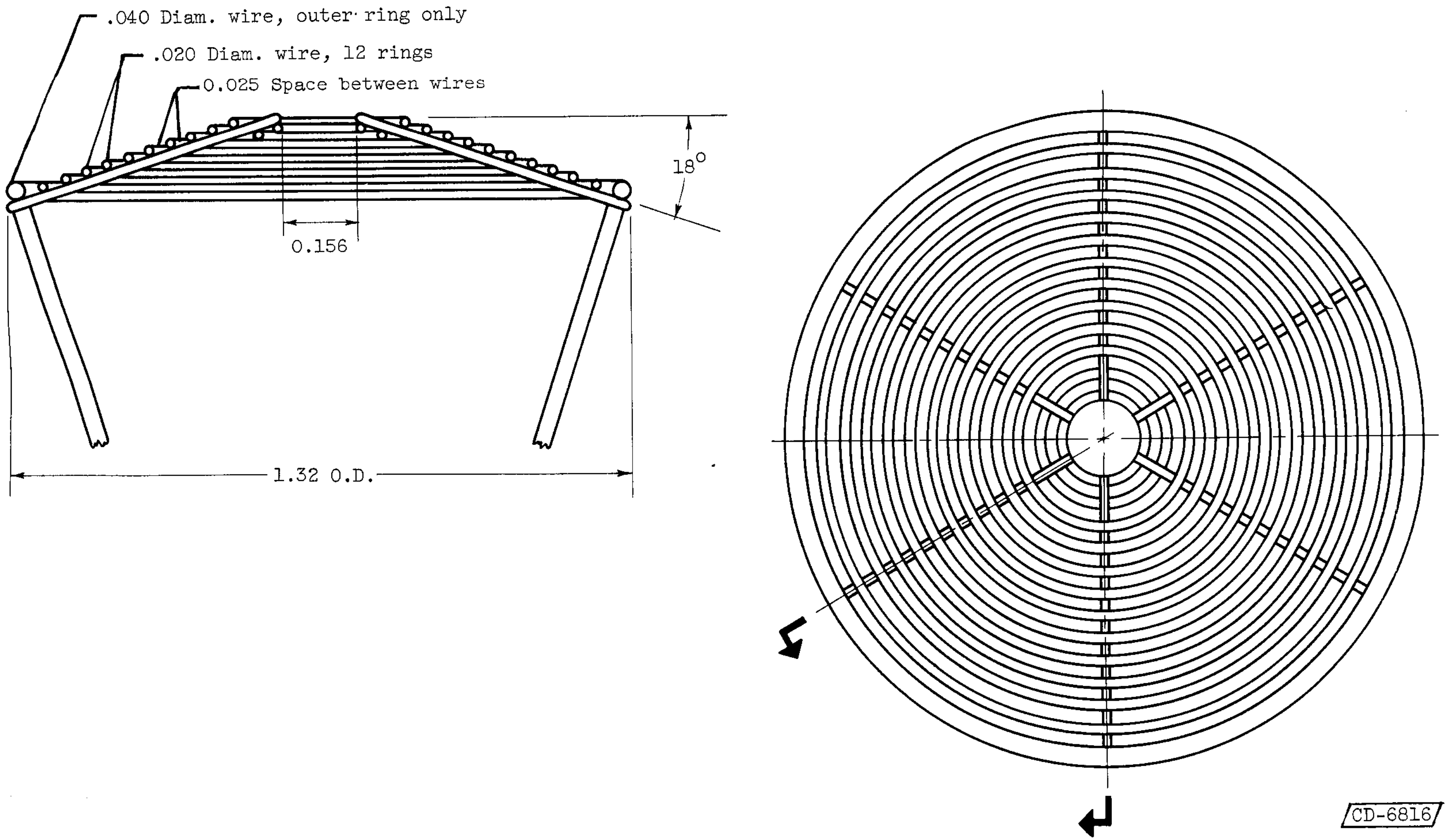
E-545



Deflector overall area	1.368 sq in.
Free area	.710 sq in.
Free-area ratio	.52

(e) Deflector 5.

Figure 5. - Continued. Deflectors for swirl-type injectors. (All dimensions in inches.)

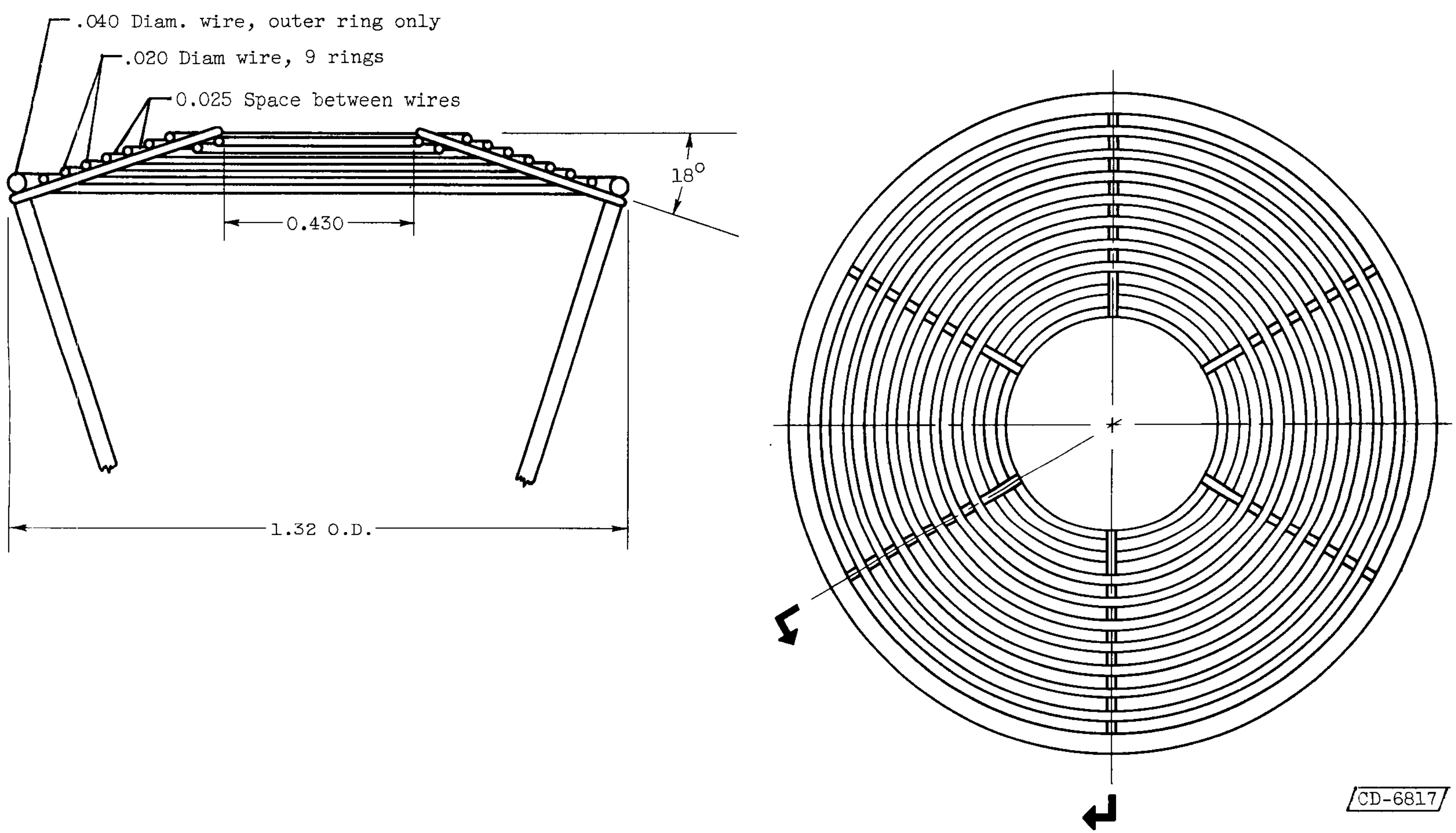


Deflector overall area	1.368 sq in.
Free area	.699 sq in.
Free-area ratio	.51

(f) Deflector 6.

Figure 5. - Continued. Deflectors for swirl-type injectors. (All dimensions in inches.)

E-343



Deflector overall area	1.368 sq in.
Free area	.751 sq in.
Free-area ratio	.55

(g) Deflector 7.

Figure 5. - Concluded. Deflectors for swirl-type injectors. (All dimensions in inches.)

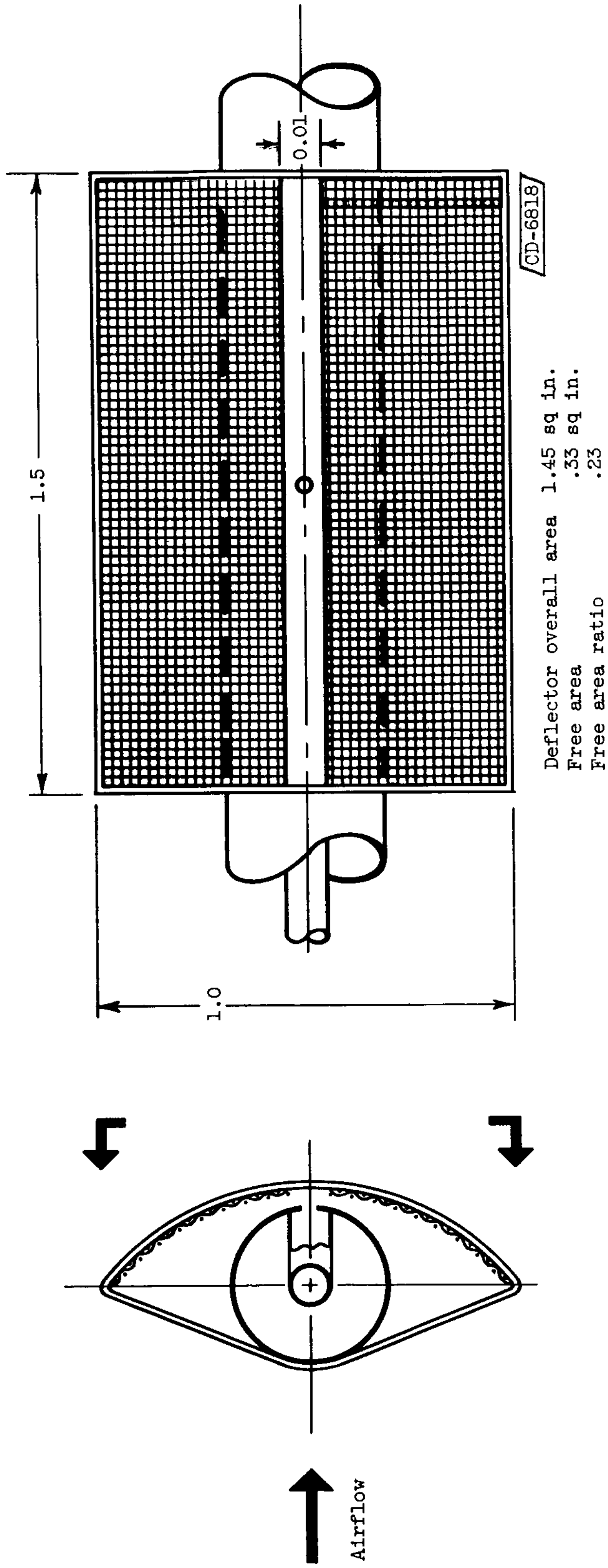
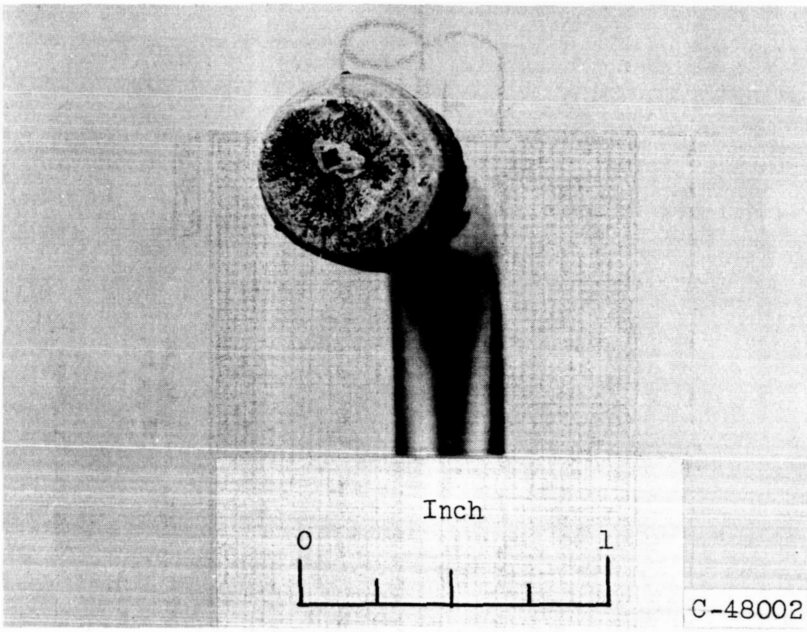
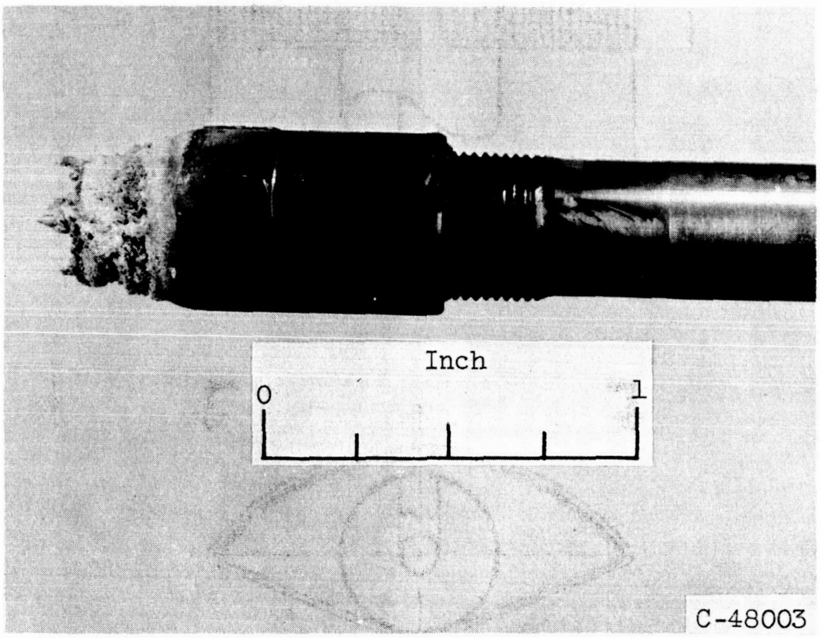


Figure 6. - Deflector for simple orifice. (All dimensions in inches.)

E-543

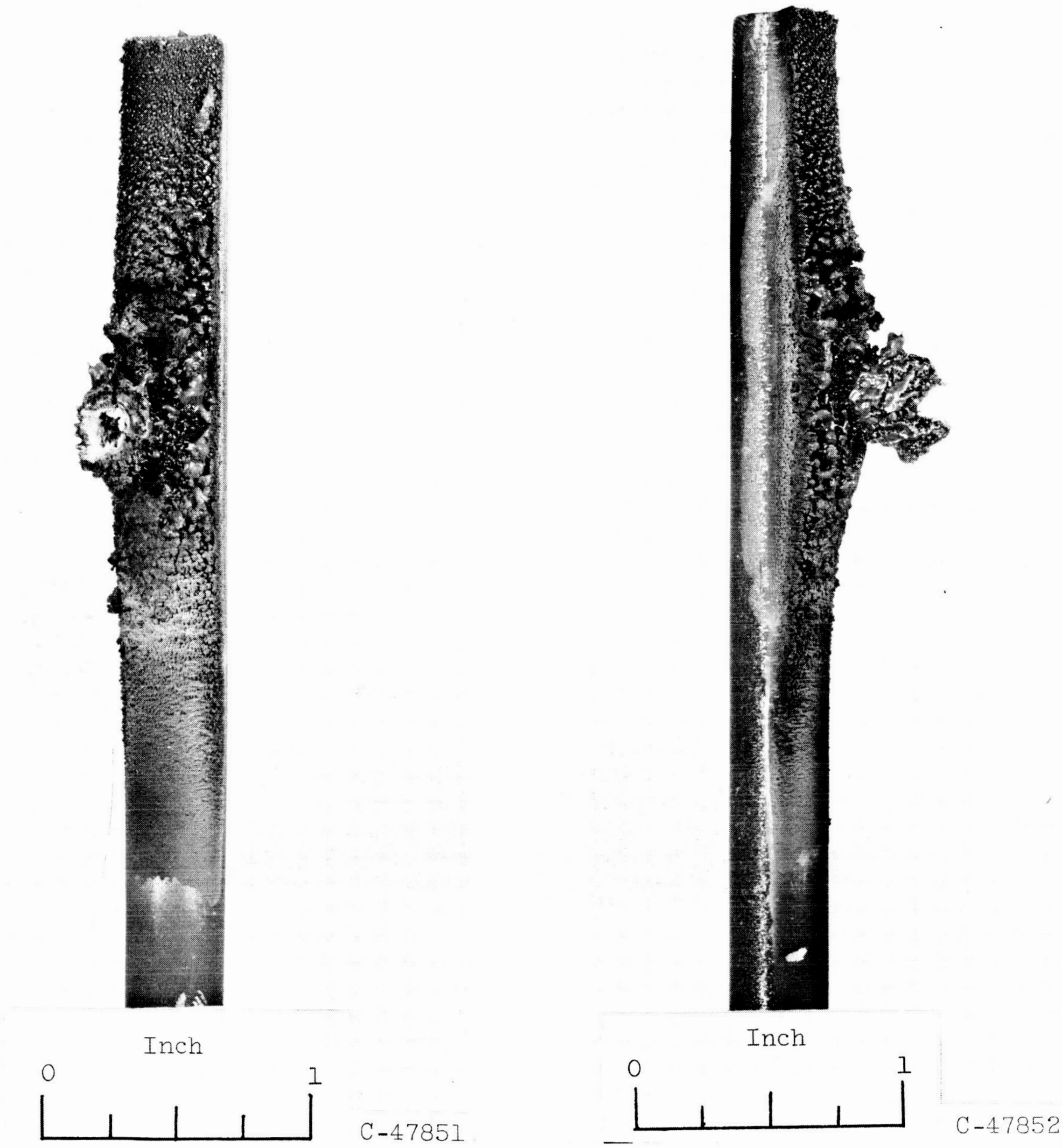




(a) Modified swirl-type injector.

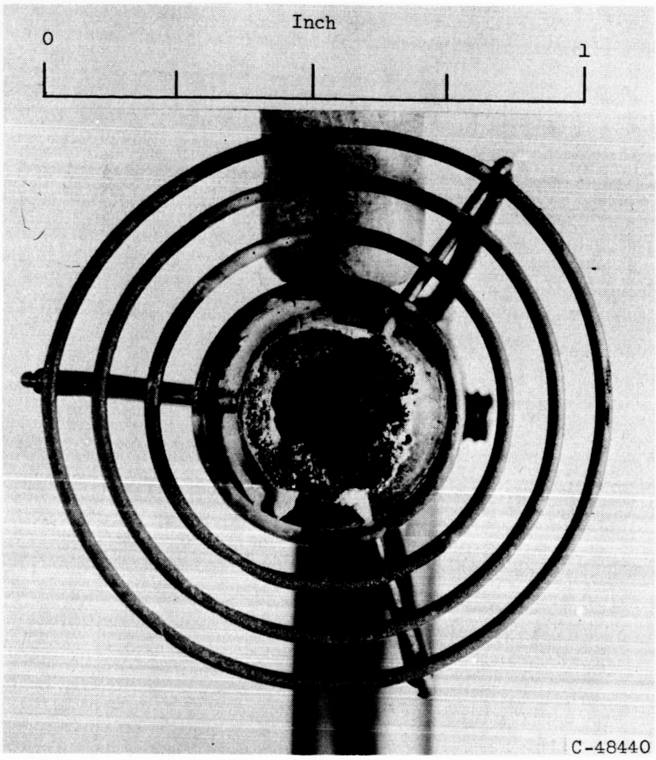
Figure 7. - Deposition on injectors (without deflector) due to HEF-2 fuel.

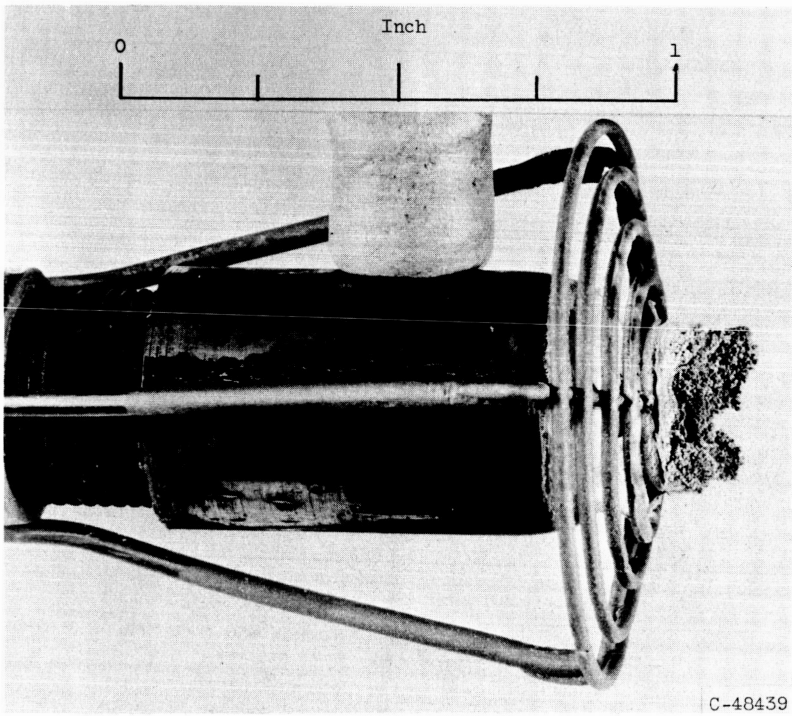
E-543



(b) Simple-orifice injector.

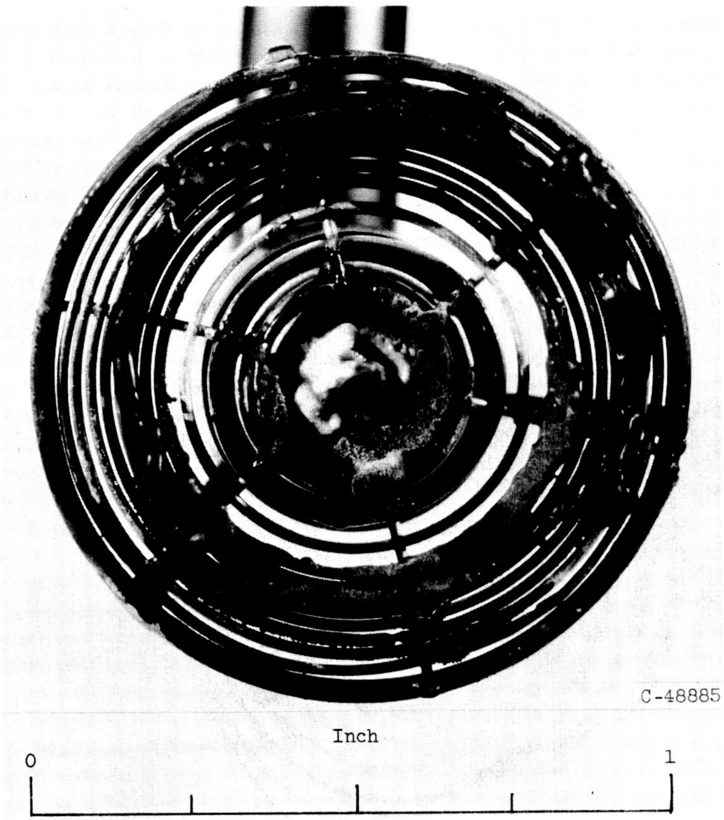
Figure 7. - Concluded. Deposition on injectors (without deflector) due to HEF-2 fuel.

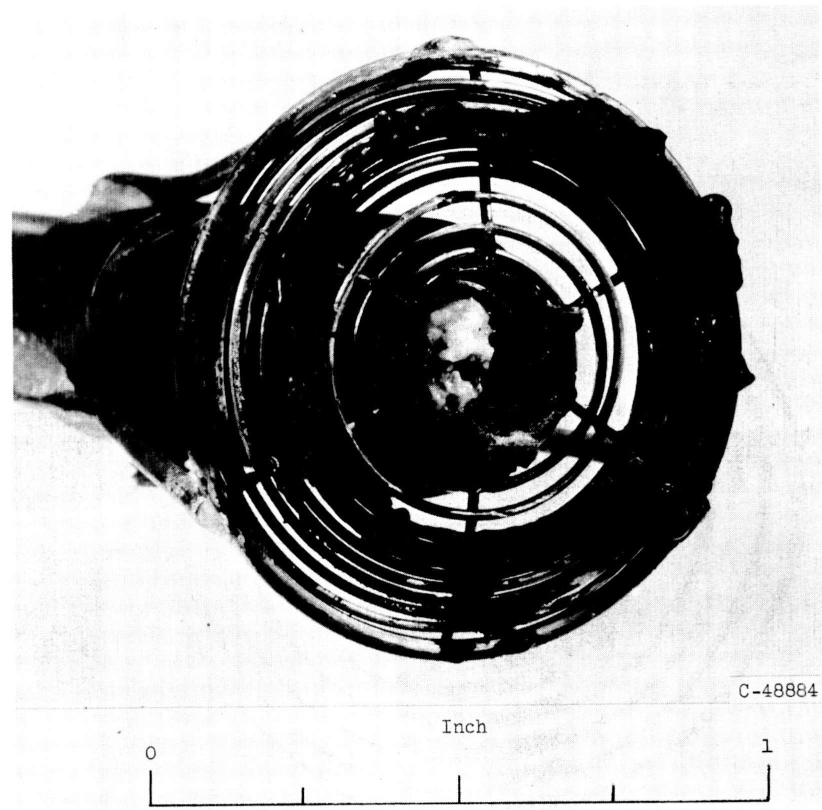




(a) Configuration 1; free-area ratio, 0.64.

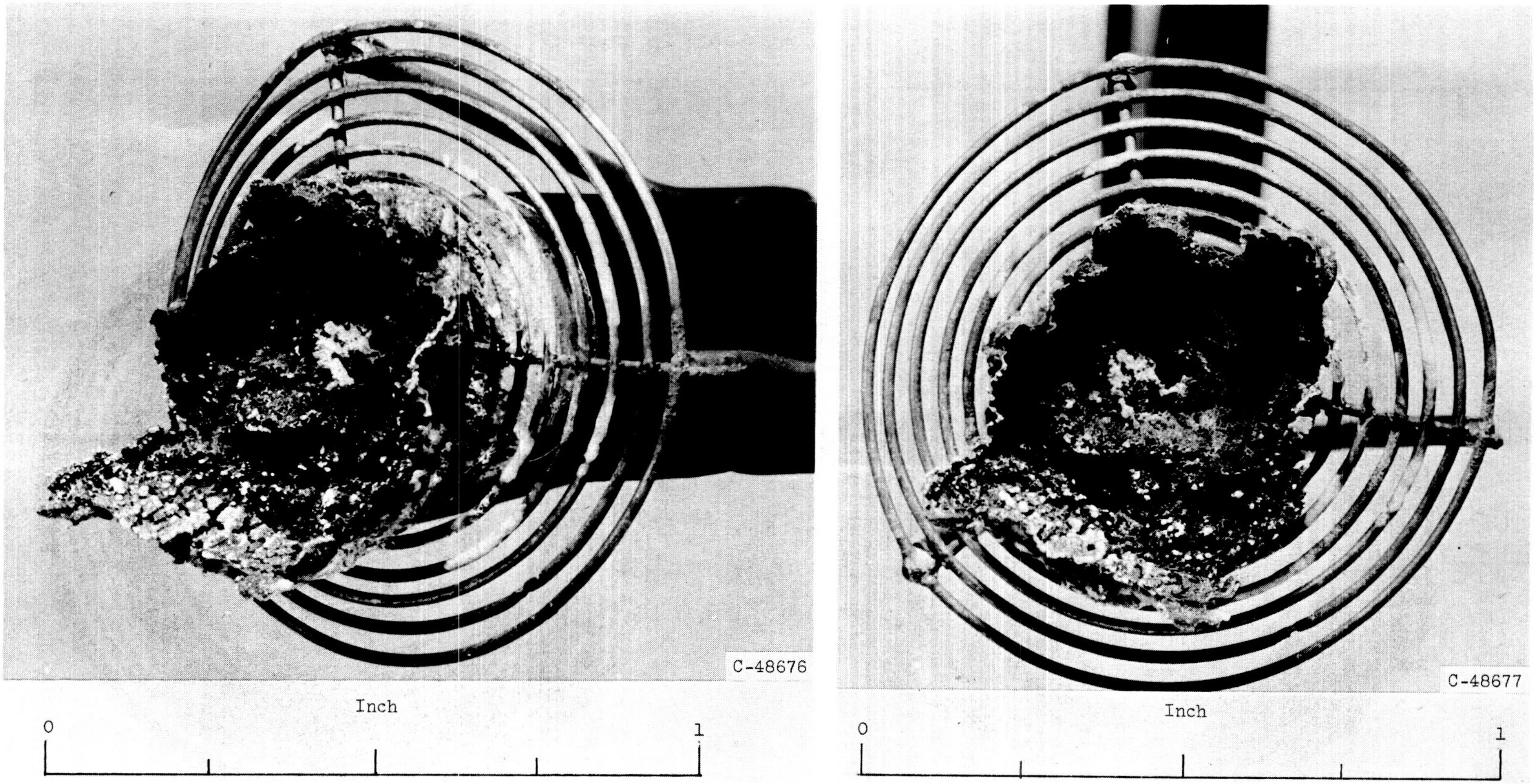
Figure 8. - Effect of deflector porosity on deposition.





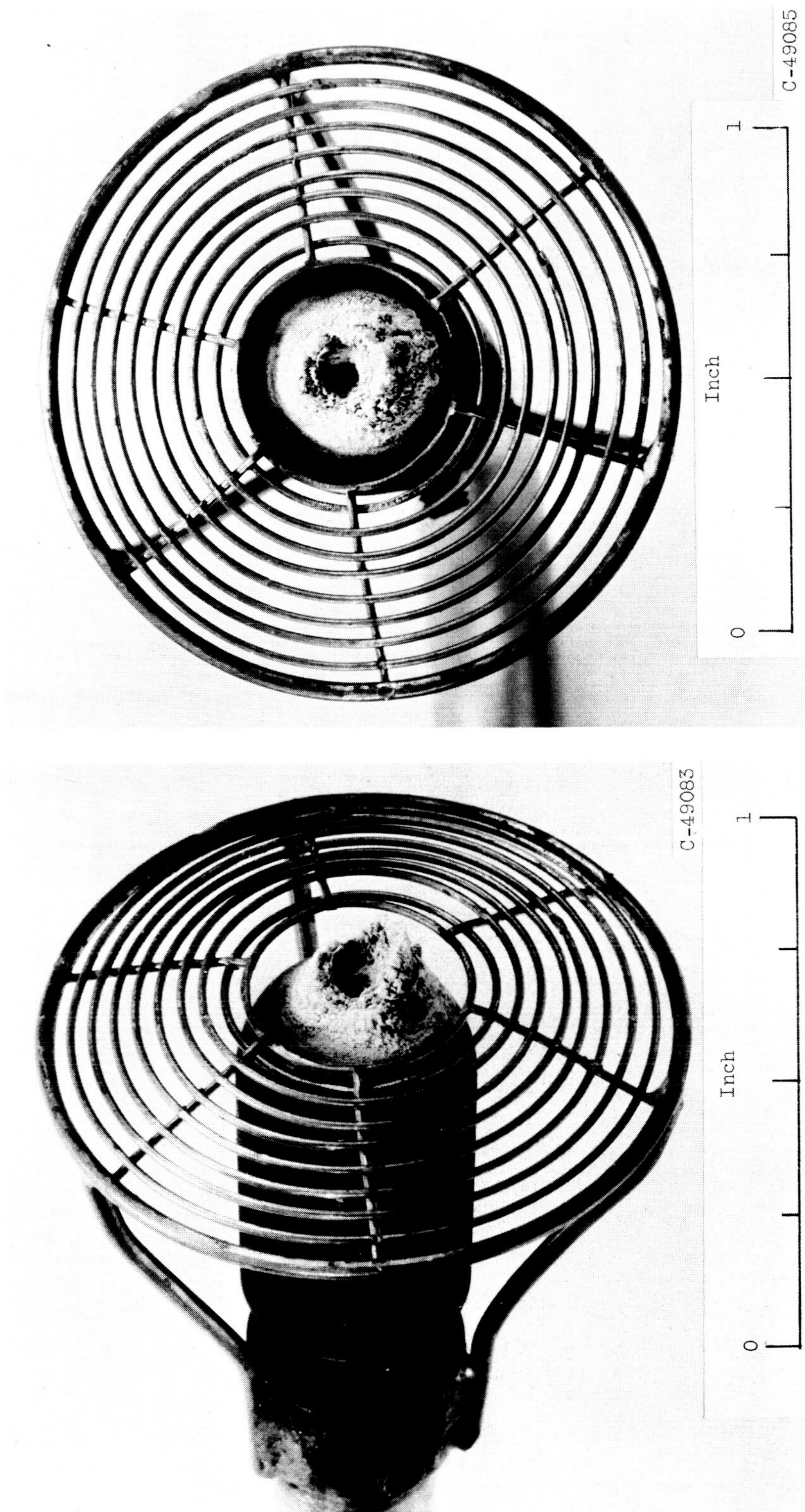
(b) Configuration 3; free-area ratio, 0.28.

Figure 8. - Concluded. Effect of deflector porosity on deposition.



(a) Configuration 2; inner-ring diameter, 0.25 inch.

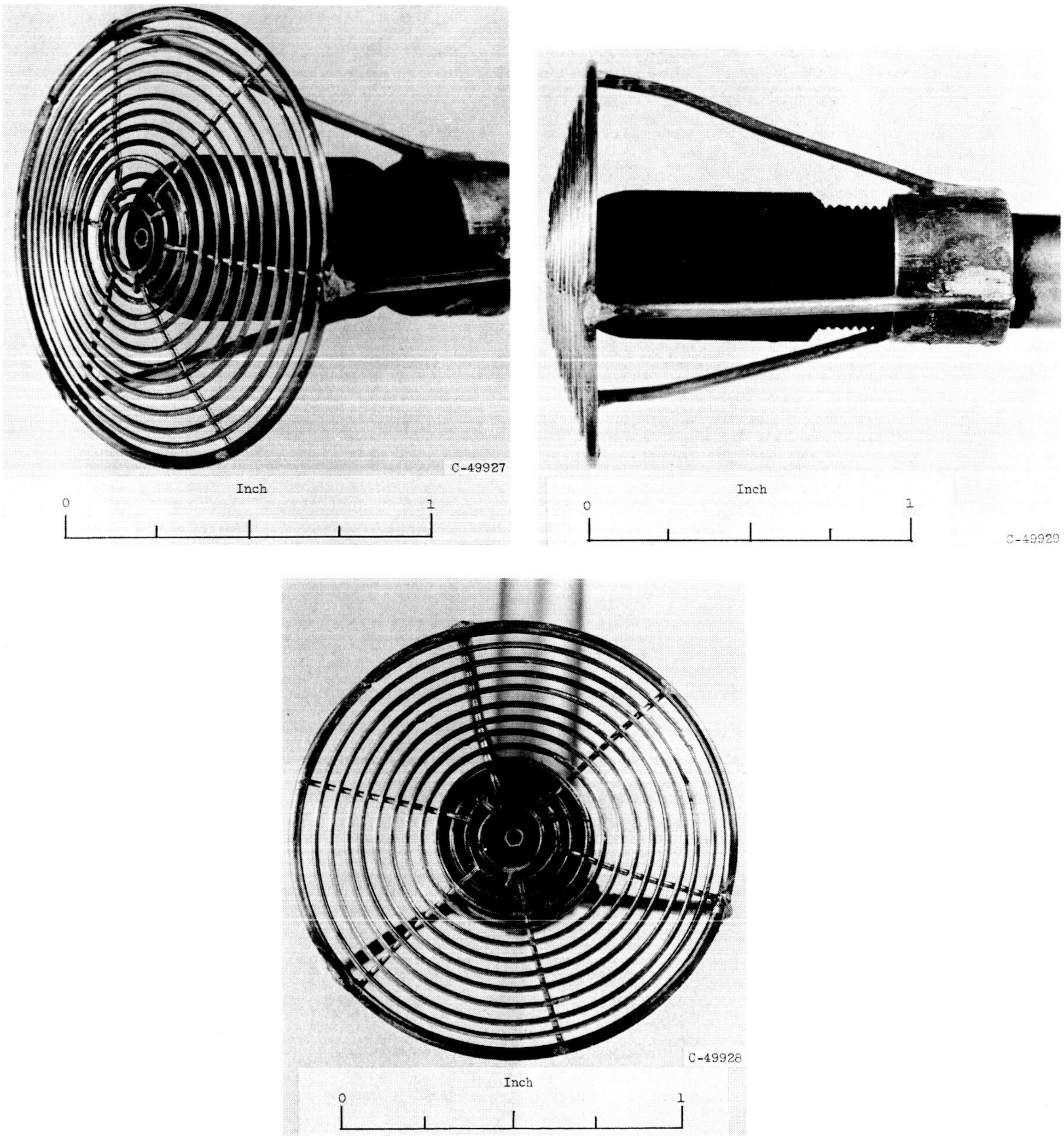
Figure 9. - Effect of deflector inner-ring diameter on deposition.



(b) Configuration 7; inner-ring diameter, 0.43 inch.

Figure 9. - Concluded. Effect of deflector inner-ring diameter on deposition.

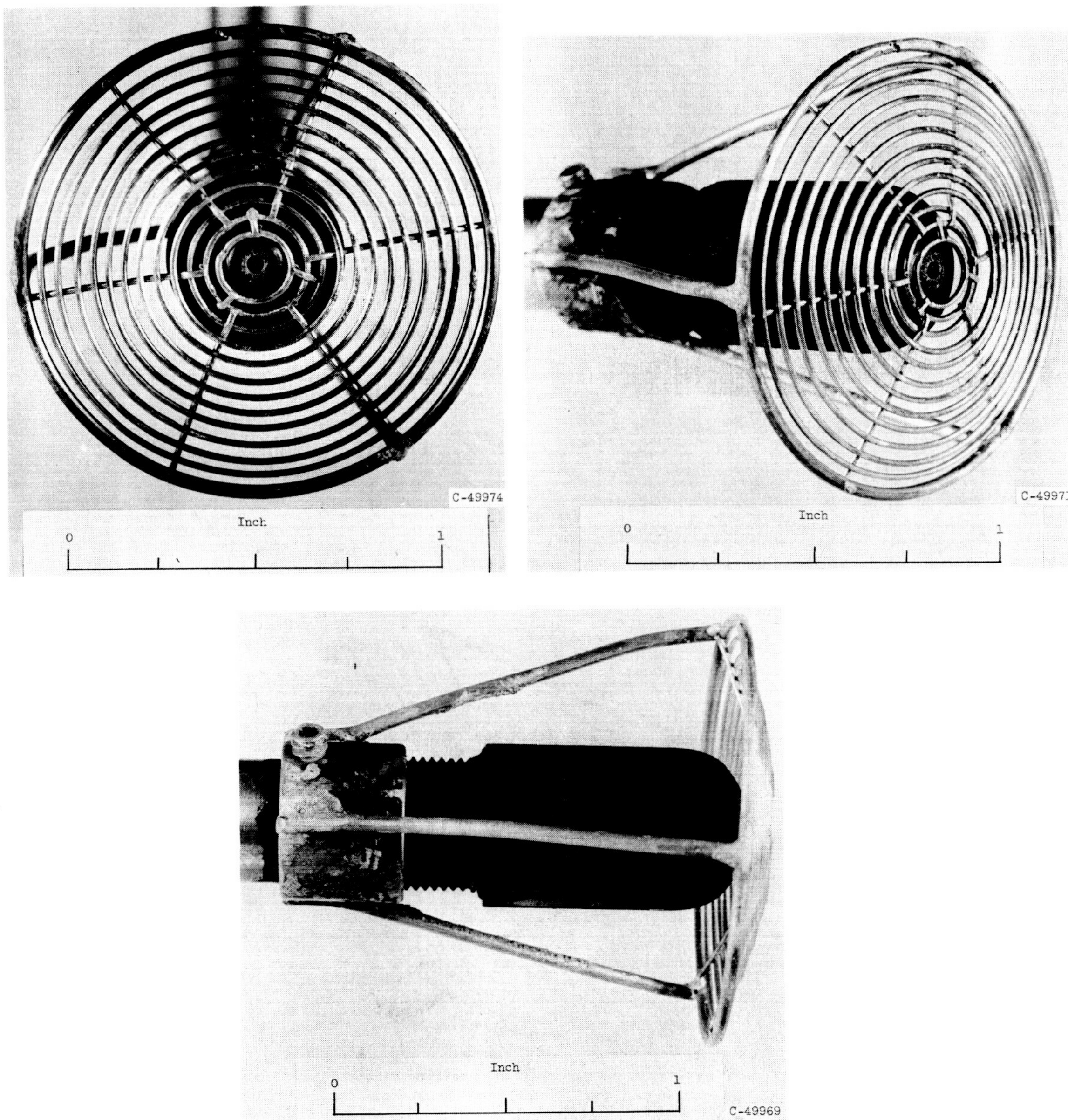
E-543



(a) Configuration 6; free-area ratio, 0.51; inner-ring diameter, 0.156 inch; outside diameter, 1.320 inch; running time, 10 minutes.

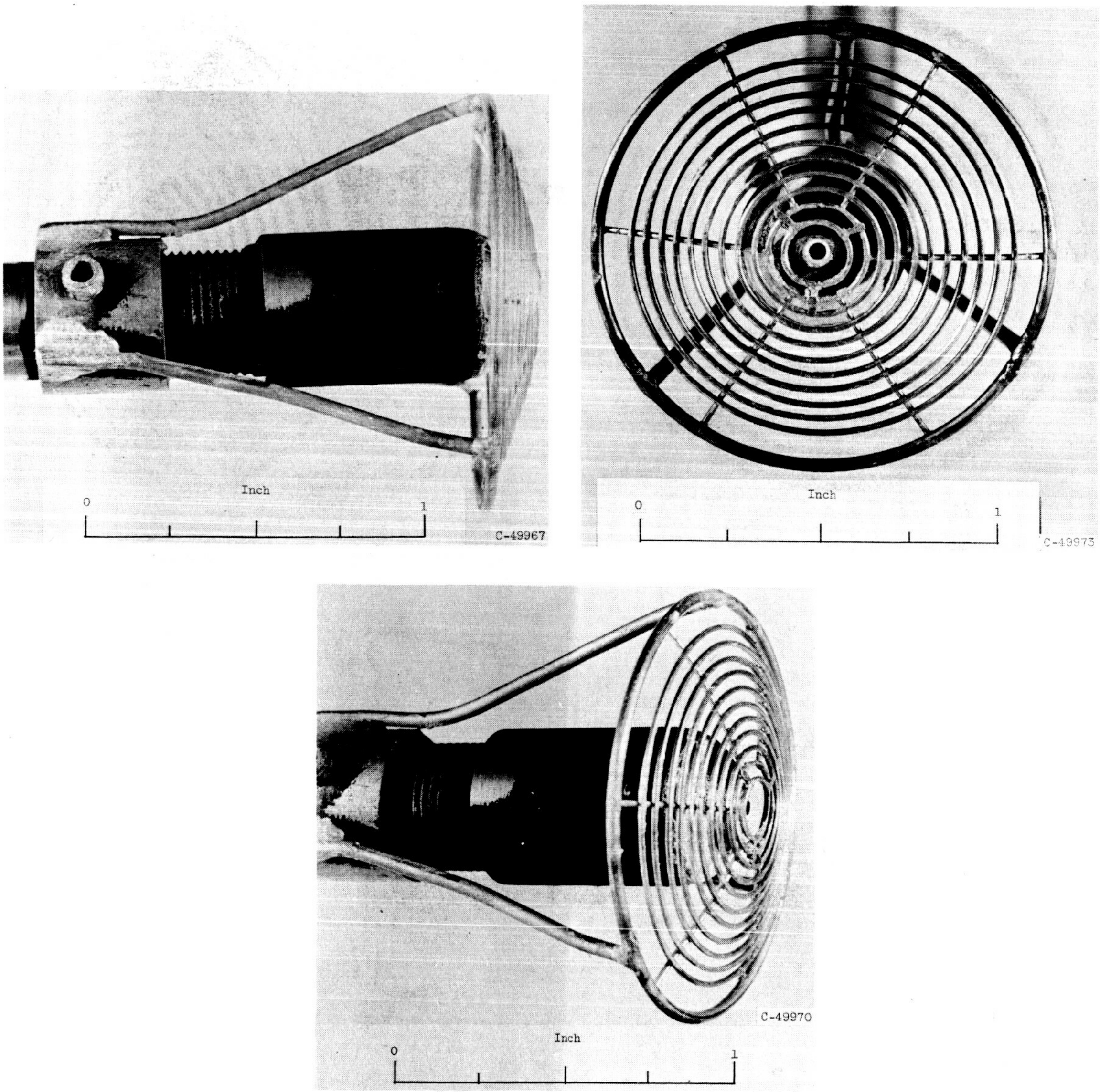
Figure 10. - Reproductions of swirl-type injector configurations after tests with HEF-2 fuel.

E-543



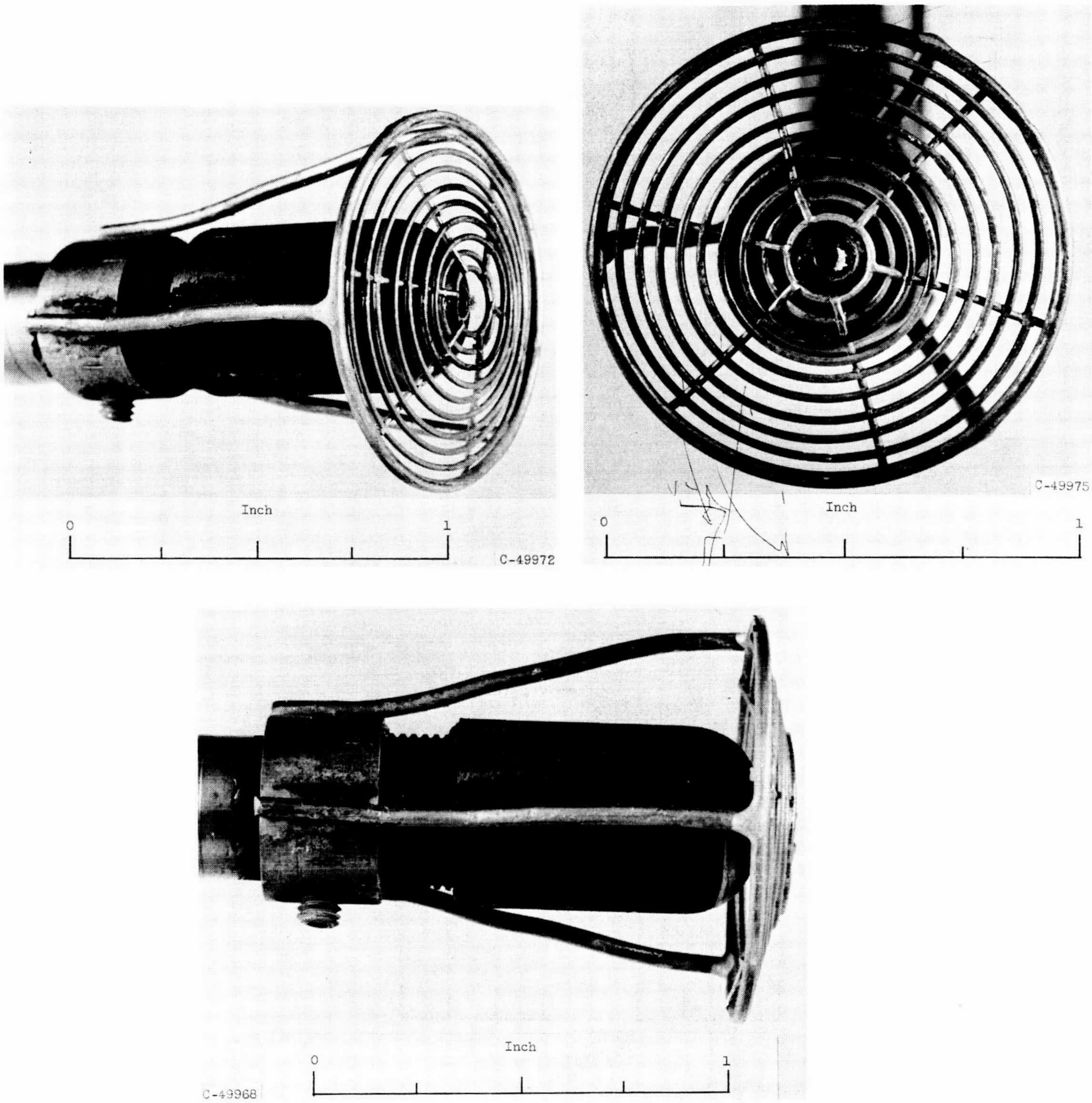
(b) Configuration 6; free-area ratio, 0.51; inner-ring diameter, 0.156 inch; outside diameter, 1.320 inches; running time, 18 minutes.

Figure 10. - Continued. Reproductions of swirl-type injector configurations after tests with HEF-2 fuel.



(c) Configuration 6; free-area ratio, 0.51; inner-ring diameter, 0.156 inch; outside diameter, 1.320 inches; running time, 18 minutes.

Figure 10. - Continued. Reproductions of swirl-type injector configurations after tests with HEF-2 fuel.



(d) Configuration 4; free-area ratio, 0.50; inner-ring diameter, 0.156 inch; outside diameter, 1.050 inches; running time, 18 minutes.

Figure 10. - Concluded. Reproductions of swirl-type injector configurations after tests with HEF-2 fuel.

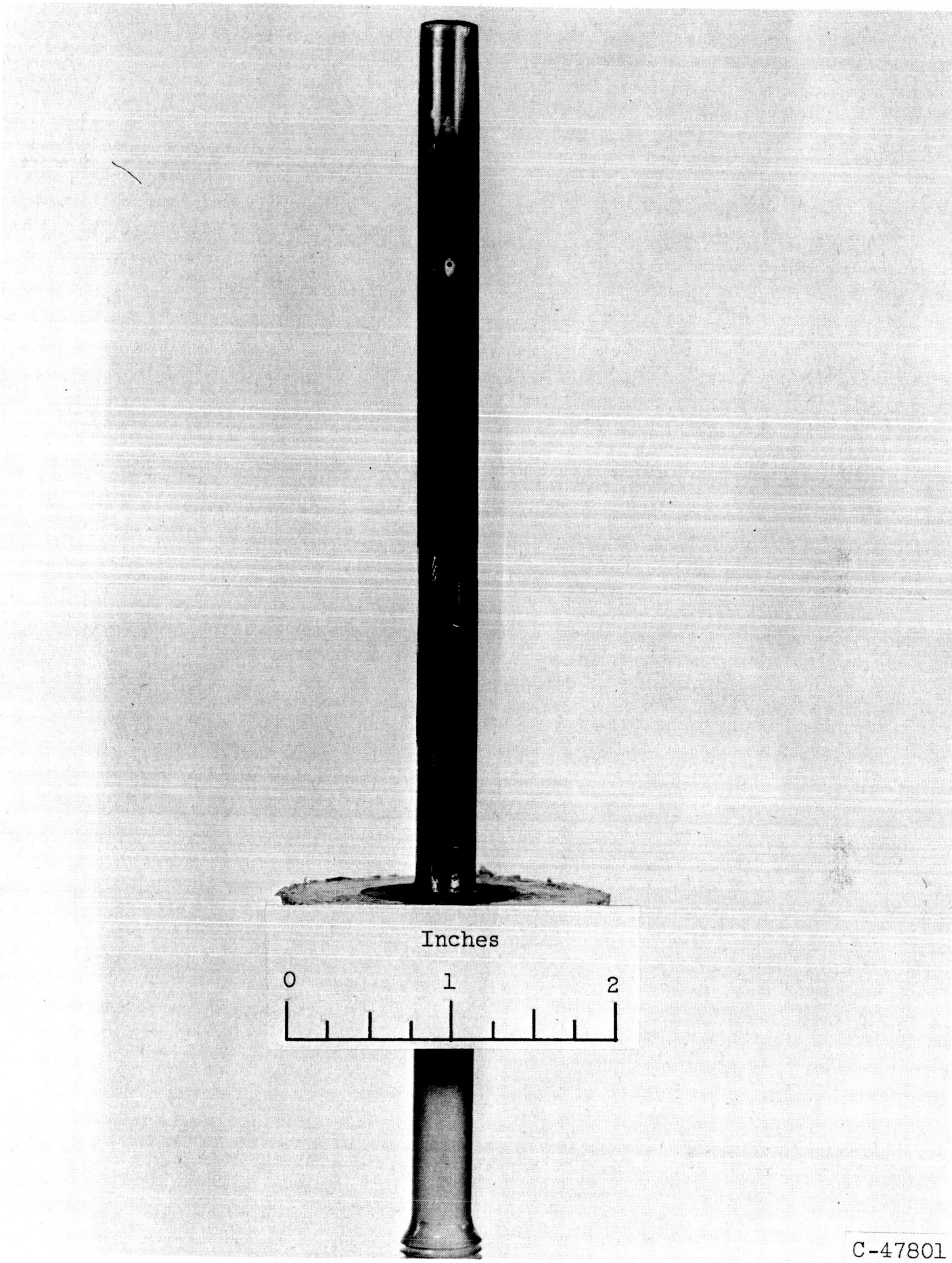


Figure 11. - Reproduction of air-atomizing simple-orifice configuration after tests with HEF-2.